Estimating Ponderosa Pine Fuel Moisture Using National Fire-Danger Rating Moisture Values

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Abstract

Comparisons were made between moisture contents of natural ponderosa pine fuels and the corresponding timelag moisture values calculated using the National Fire-Danger Rating System. The two variables correlated well at the driest moisture levels, but precipitation influenced each differently. Empirically derived equations permit adequate estimates of actual fuel moisture for burning projects.

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[1]Headquarters is in Fort Collins, in cooperation with Colorado State University. Research reported here was conducted at the Station's Research Work Unit at Tempe, in cooperation with Arizona State University.

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Management Implications

National forests maintain fire weather stations to monitor changing weather conditions for fire-danger forecasting. The weather elements, together with fuel moisture contents estimated from them, indicate potential wildfire behavior. This study compared actual fuel moisture contents from a ponderosa pine (*Pinus ponderosa* ~~var.~~ *arizonica*) stand in southeastern Arizona to calculated fuel moisture contents from the National Fire-Danger Rating System (NFDRS) using data from nearby weather stations. These comparisons were used to evaluate the accuracy of the fuel moisture models in estimating actual fuel moisture and to develop equations, utilizing NFDRS moisture values, which would provide better estimates of fuel moisture for use in prescribed fire planning.

The moisture content of the L (litter) layer needles is important in determining whether ignition will occur and how intensely and rapidly a fire will burn in these natural fuels. Calculated 1-hour timelag fuel moisture (1-h TL FM) proved to be a good indicator of L layer needle moisture below 10%. At the moist end of the data range, where fuels had been recently influenced by precipitation, the correlation held but the one-to-one relationship failed. One-half-inch fuel stick moisture also correlated well with L layer needle moisture. Because precipitation affected the moisture content of the fuel sticks and L layer needles differently, an equation was developed for the data not influenced by precipitation as well as for the entire data range. These equations proved to be the most accurate estimators of L layer moisture content; the equation for the fuel stick moisture range of 3% to 12% should be used when rain has not been a factor for at least 24 hours.

Within certain weather limits, the moisture content of the H (humus) layer determines how much of the forest floor will be consumed by fire. H layer moisture content can be estimated using 100-h TL FM and the developed equation.

Fair agreement was found between the moisture content of smaller woody fuels and the corresponding NFDRS timelag fuel moisture content. In all cases, a one-to-one relationship between actual and calculated moisture contents was not found where precipitation was influential. However, at the lowest moisture levels when there had been no precipitation for 24 hours, the one-to-one relationship was approached.

Even though the NFDRS moisture estimates were not exact over the entire moisture range for this study site, these estimates were quite accurate under the drier conditions. This is where precise information concerning potential wildfire behavior is critical. In addition, the equations presented here seem to be sufficiently accurate to estimate fuel moisture conditions which, when combined with weather data, could be very useful in prescribed burning. The equations should be applicable to southeastern Arizona ponderosa pine stands similar to those described here. Application to other areas will require further testing.

Introduction

Fuel moisture is one of the most important parameters determining fuel ignitability, rate of combustion, and amount of consumption. To estimate wildfire behavior variables, such as fire intensity, flame lengths, and rate of spread, the moisture content of the fuels involved must be known (Albini 1976). The moisture contents of various size fuels are also key values for the National Fire-Danger Rating System (Deeming et al. 1977). In addition, fuel moisture plays a major role in determining the success of prescribed fire. Amount of fuel consumption has been directly related to fuel moisture in understory burning in the Southeast (Hough 1968), the Northeast (Van Wagner 1972), the Northwest (Norum 1977), and the Southwest (Harrington 1981).

Attempts have been made to correlate calculated fire danger or hazard indices with actual fuel moisture contents, so that readily available and reliable moisture estimations could be made. Morris (1966) offered guidelines for predicting successful slash burning in the Pacific Northwest using fuel moisture stick values. In British Columbia, poor relationships were found between hazard stick readings and slash moisture contents simply because the wetting and drying characteristics of the sticks were unlike those of the slash (Péck 1969). A fair correlation was shown between the buildup index of the 1964 NFDRS and duff moisture of southeastern pine stands (Johnson 1968). Bradshaw (1978) reported weak relationships between duff moisture in western Montana western larch—Douglas-fir (*Larix occidentalis* - *Pseudotsuga menziesii*) stands and the 10-, 100-, 1,000-hour timelag moisture values, the buildup index, and the energy release component of the 1978 NFDRS. In a field test of a duff moisture prediction model based on weather parameters, Frandsen and Bradshaw (1980) found fair agreement between predicted and measured moisture content below 50% in the lower duff. Insensitivity of the model to duff depth variation and liquid water transport were the reasons given for poor predictability above 50% moisture content. Jarvis and Tucker (1968) found the Canadian Drought Index to be a good predictor of L and F horizon moisture content in cut-over white spruce-aspen stands (*Picea glauca* - *Populus tremuloides*). In Pacific Northwest Douglas-fir stands, good agreement was found between

the NFDRS 1,000-h TL FM and lower duff moisture content, percent of duff reduction, depth of duff reduction, and mineral soil exposed by fire (Sandberg 1980).

Gravimetric moisture determination by direct fuel sampling is standard procedure for most research and some administrative fire-use projects where precision is needed. Because this method is time consuming and requires special equipment, research was conducted to test the accuracy of the National Fire-Danger Rating System moisture models, and to empirically develop equations for improved fuel moisture prediction.

Study Site

This study was conducted in conjunction with a prescribed burning project in the Santa Catalina Mountains of southeastern Arizona (Harrington 1981). The study site had a southwestern exposure with 30-50% slopes, in a stand composed primarily of ponderosa pine. Other species present were southwestern white pine (*Pinus strobiformus*), Douglas-fir, and silver leaf oak (*Quercus hypoleucoides*).

The stand consisted basically of two distinct maturity groups (fig. 1). Open groups were dominated by large, old growth ponderosa pine with a sparse pine seedling understory. These groups averaged about 600 trees per acre with 206 square feet of basal area per acre. Surface fuels were exposed to many hours of direct sunlight and direct rainfall. Closed groups were characterized by dense, overstocked clumps of ponderosa pine saplings, often referred to as "dog-hair thickets." The average density was 3,500 trees per acre with a basal area of 186 square feet per acre. With the thick canopy cover, fuels were exposed to little sunlight, and rainfall was dispersed through the canopy. Because of the obvious group differences, sampling was stratified by maturity group.

Methods

Sampling for fuel moisture determination began on June 6 and continued through August 22. Collections were made during the same time period (1300–1500 MST) each sampling date. L layer needles[2] were sampled daily because of their short response time and exposure to steep temperature and vapor pressure gradients. In addition, the following fuels were collected twice weekly: F layer needles,[3] H layer humus,[4] 0- to 0.25-inch twigs, 0.25- to 1-inch twigs, and 1- to 3-inch branchwood. Six samples of each fuel were collected from each of the two overstory groups within a 3-acre stand. Each sample was a composite of four or five subsamples. All moisture determinations were made gravimetrically.

Figure 1.—Ponderosa pine stand with two maturity groups; open group is on the right and closed group is on the left.

A weather station equipped with a recording rain gage and hygrothermograph was set up on the site. Fuel moisture stick values, temperature, precipitation, and relative humidity were monitored at the Palisades fire weather station a few hundred yards from the study site.

Results and Discussion

L Layer Moisture Content

The moisture contents of the L layer needles and H layer humus are considered the most important moisture variables in the burning of the forest floor at this site (Harrington 1981). L layer moisture content strongly influences ignitability, fire intensity, and rate of spread. H layer moisture content is a major factor in determining the amount of the forest floor which will be consumed by a fire, because more than 50% of the total loading occurred in this layer.[5] The fermentation (F) layer generally completes the moisture gradient between the L and H layers. Although the F layer moisture content has some effect on rates and amounts of forest floor consumption, its position and weight make it less influential than the surrounding layers.

Deeming et al. (1977) stated that the l-hour timelag fuel moisture content (1-h TL FM) calculated in the 1978 NFDRS corresponds to the moisture content of cylindrical woody fuels less than 0.25-inch in diameter and of litter less than 0.25-inch deep. The latter would include the L layer needles. Comparison of calculated 1-h TL FM to actual L layer needle moisture contents from the open group is shown in figure 2.

The coefficients of determination (r^2) and standard errors ($S_{y \cdot x}$) indicate good agreement between the two variables (fig. 2). However, the relationship between the calculated 1-h TL FM and the actual L layer moisture in the open groups is not one-to-one. One reason for this is that freshly cast pine needles have a timelag of about 4 hours rather than 1 hour, and needle beds have a response time of 2.5 hours to 7 hours depending on bulk density and solar influence (Anderson

[2] *The L layer needles are the most recently fallen, unweathered, light-brown needles.*

[3] *The F layer needles are in the early stages of decomposition and weathering with a distinct grayish color.*

[4] *The H layer humus consists of fuel in advanced stages of decomposition.*

[5] *Data on file, Fuel Management Project, Tempe, Ariz.*

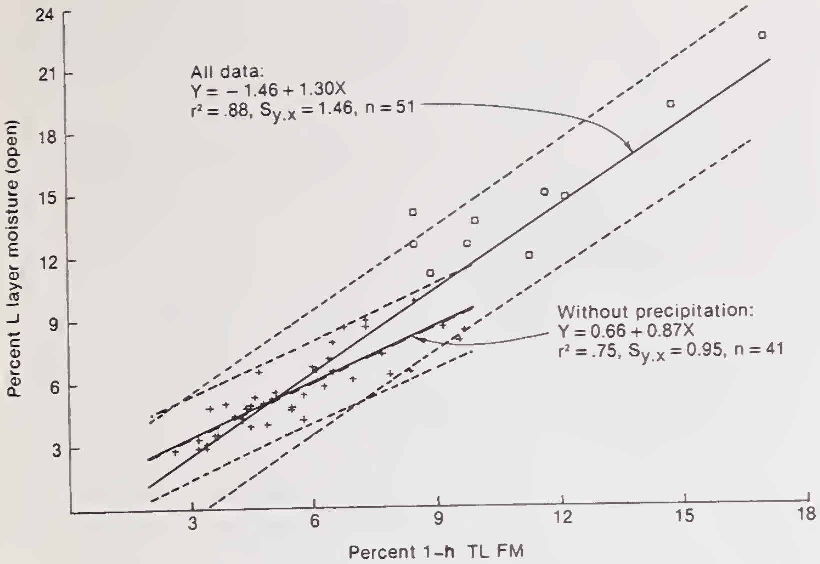

Figure 2.—Relationship of 1-h TL FM and open group L layer needle moisture with (0) and without (+) precipitation influences. Confidence bands are included, $P = 0.05$.

et al. 1978). As needles age, their timelag decreases (Simard 1968b), approaching 1 hour.

Figure 3 compares the daily trace of 1-h TL FM with open group L layer needle moisture content. The dates of four major precipitation periods are represented by the resulting high fuel moisture. When influenced by rain, the actual needle moisture content rose to higher levels than the calculated 1-h TL FM. However, the 1-h TL FM fluctuated more than actual fuel moisture when influenced by changing vapor pressure (relative humidity). This was likely a result of the greater-than-1-hour timelag of fresh needles and needle beds.

One environmental condition which caused actual and calculated fuel moisture to differ was an abrupt change in relative humidity at observation time (1300 MST), which is used to calculate 1-h TL FM (Burgan et al. 1977). Examples of this are shown in figure 4. On July 13, the humidity increased rapidly, peaked at about 0800 MST, then tapered off slowly so that at observation time it was still high (60%). The 1-h TL FM was higher than needle moisture because the latter could not respond rapidly to the abrupt humidity change. An opposite situation occurred on August 14 when a rapid decrease in humidity near observation

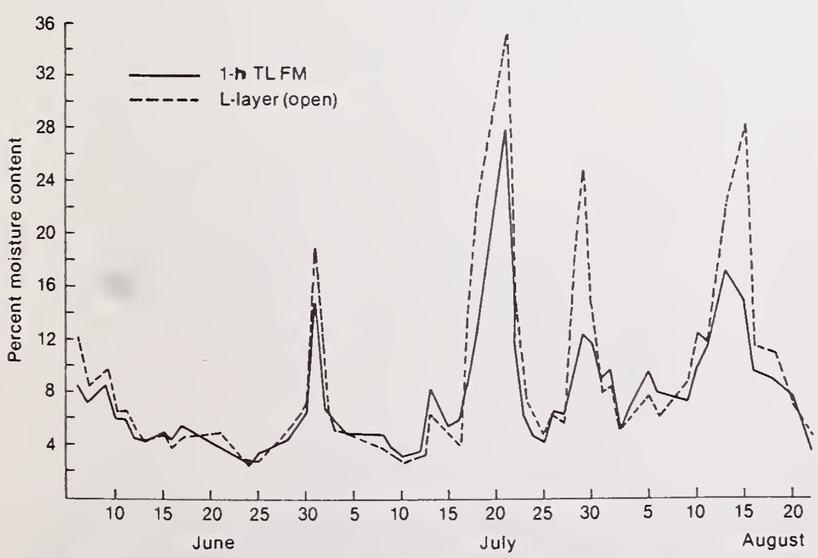

Figure 3.—A 78-day comparison of L layer needle moisture content from open groups and 1-h TL FM.

time caused a lower 1-h TL FM because, again, the needle fuels do not respond to moisture changes as rapidly as air does (humidity).

Because of the complexity of the required calculations, precipitation is not part of the computations for 1-h TL FM (Fosberg and Deeming 1971). Therefore both direct and lingering effects of precipitation might cause actual fuel moisture to differ from 1-h TL FM. When the data points which represent fuel moisture influenced by precipitation within the previous 24 hours were removed, the resulting regression (fig. 2, +'s) yields a better estimator of L layer moisture in the 3% to 10% range than the regression of all points. Reasons for this are that higher moisture data are outside the critical 3% to 10% range, which contains nearly the entire fine fuel moisture range where fire will spread easily and

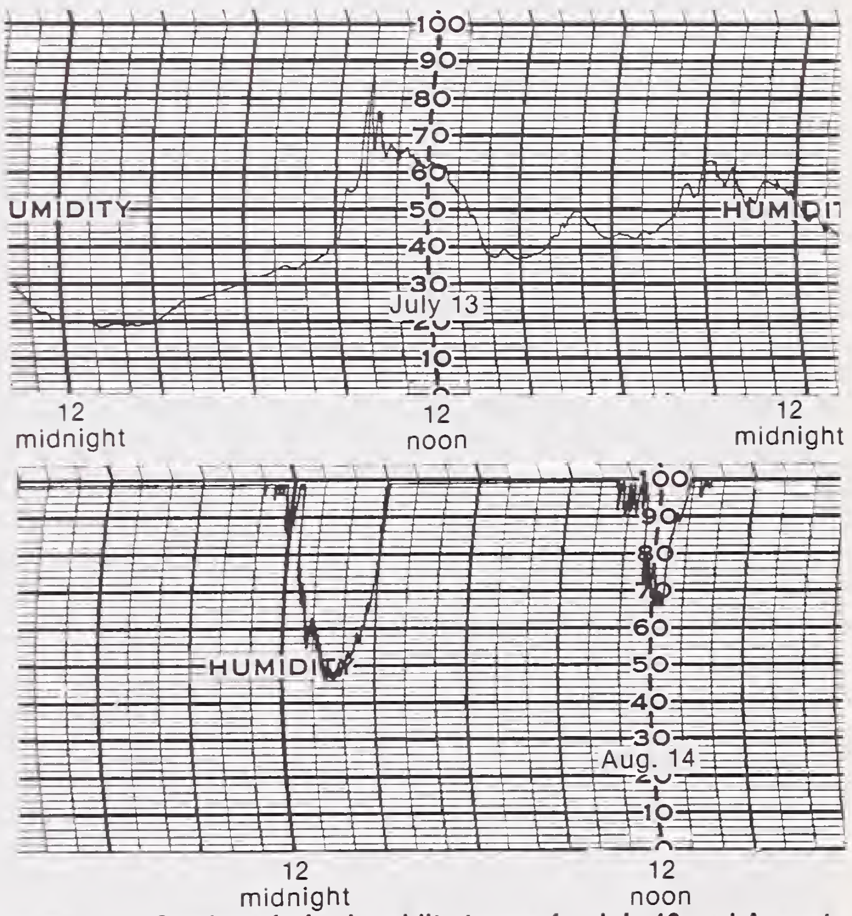

Figure 4.—On-site relative humidity traces for July 13 and August 14, 1979.

burn fuels completely; that the no-precipitation regression is less variable (narrower confidence bands); and that this regression yields an $X = Y$ relationship (i.e., tests indicate the slope approximately equals one and the Y-intercept approximately equals zero).

Agreement between 1-h TL FM and L layer needle moisture in the closed groups was also quite good (fig. 5). The slope of the regression was greater than for the open groups indicating a higher litter moisture in the closed groups for given 1-h TL FM. This was because of the constant shade, lower temperatures, and higher humidities associated with a closed stand (Simard 1968c, Countryman 1977). Removing fuel moisture points influenced by precipitation within the previous 24 hours reduced the slope of the regression and again produced a slightly better predictor of L layer moisture in the important burning range of 3% to 12%.

In the determination of fuel moisture for precribed

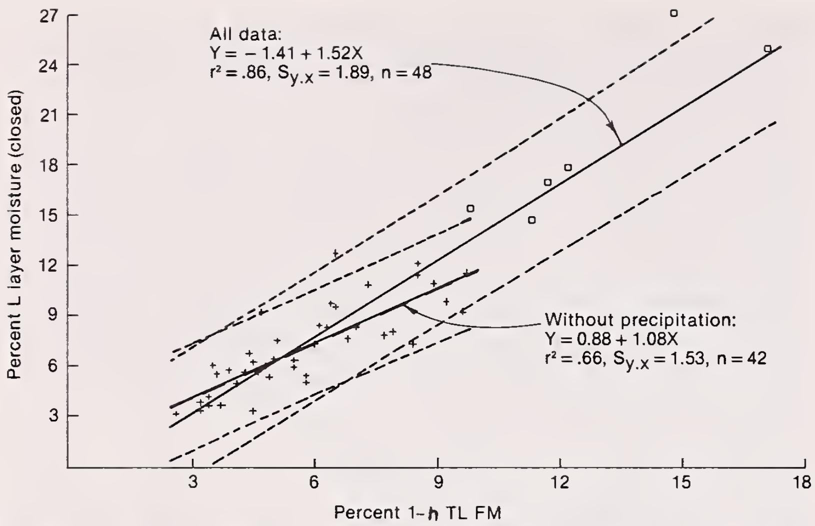

Figure 5.—Relationship of 1-h TL FM and closed group L layer needle moisture content with (0) and without (+) precipitation influences. Confidence bands are included, $P = 0.05$.

burning projects, an overestimation could result in serious consequences, such as severe fire effects or even escape fires, especially near the driest prescription limits. The regressions for both open and closed groups (figs. 2 and 5) were found to overestimate fuel moisture in situations where the 1-h TL FM was greater than the 10-h TL FM. The fuel moistures were 1% to 3% lower than predicted when this occurred.

Good agreement was found between the L layer needle moisture content of the open and closed groups. The regression equation with X being open group moisture content and Y being closed group moisture content was:

$$Y = 0.44 + 1.16X \ (r^2 = 0.92, S_{y \cdot x} = 1.41, n = 48)$$

Removing the moisture values influence by recent rainfall had little effect on the relationship:

$$Y = 0.54 + 1.15X \ (r^2 = 0.82, S_{y \cdot x} = 1.08, n = 41)$$

Because freshly cast needles and needle beds have moisture timelags greater than 1 hour, the relationship of measured L layer needle moisture with fuel stick moisture and 10-h TL FM was tested. Fuel stick moisture correlated slightly better with actual open group needle moisture (fig. 6) than did 1-h TL FM (fig. 2). Within the majority of the data range, the fuel stick moisture regression produced a one-to-one relationship between fuel stick and L layer needle moisture. This relationship did not hold for the 1-h TL FM regression utilizing the entire data range (fig. 2) because precipitation is not directly accounted for as it is with the fuel stick. Further, even though the fuel stick represents a 10-hour timelag fuel, its position above the forest floor permits it to be influenced on all surfaces by conditions of the surrounding air. The L layer is influenced by conditions of the forest floor below as well as the air above, perhaps allowing its moisture content in this range to change as does the fuel stick's. As before, when those points influenced by precipitation are removed, the new regression with narrower confidence bands becomes the preferred estimator of L layer moisture in the 3% to 10% range (fig. 6) where most prescribed and wildfires occur.

The correlation and standard error were poorer using 10-h TL FM ($r^2 = 0.81, S_{y \cdot x} = 1.88$) rather than fuel stick moisture ($r^2 = 0.90, S_{y \cdot x} = 1.33$) in the regression with L layer moisture. This suggests that the conversion of fuel stick weights to 10-h TL FM based on stick age (Burgan et al. 1977) may have overcompensated as Haines and Frost (1978) indicated.

Figure 7 shows the regression equations of closed group L layer needle moisture with both fuel stick moisture, and fuel stick moisture not influenced by rain. Again, fuel stick moisture proved to be a better indicator of needle moisture than 1-h TL FM (fig. 5). Within the 3% to 12% moisture range, the equation eliminating precipitation influence is the recommended predictor. In an attempt to develop a better moisture indicator in the canopy-covered closed groups, a new 1-h TL FM was calculated assuming a continually cloudy condition by holding the state of weather to a constant value of three (greater than 90% cloud cover). This new 1-h TL FM had a poorer correlation ($r^2 = 0.83, S_{y \cdot x} = 2.08$) with L layer moisture over the entire data range than either 1-h TL FM (fig. 5) or fuel stick moisture (fig. 7). However, over the moisture range not influenced by precipitation (3% to 12%), the regression equation using the new 1-h TL FM,

$$Y = 0.56 + 0.97X \ (r^2 = 0.75, S_{y \cdot x} = 1.26, n = 41)$$

had as good an agreement with L layer moisture as fuel stick moisture (fig. 7) and better than the original 1-h TL FM (fig. 5). This equation also produced a one-to-one relationship between the independent and dependent variables, as indicated by tests showing the slope approximately equals one and the Y-intercept approximately equals zero.

The best predictor of L layer fuel moisture in both groups appears to be the fuel stick. More of the variation in L layer moisture was associated with fuel stick moisture variation than with 1-h TL FM variation. Deviations from the regression were also minimized. Most burning prescriptions, such as the preliminary plan for

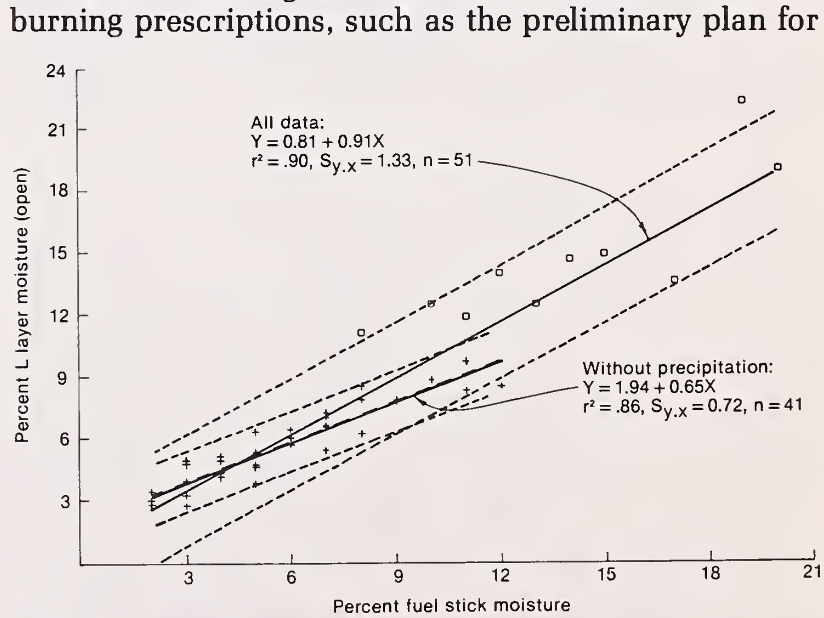

Figure 6.—Relationship of fuel stick moisture content and open group L layer needle moisture content with (0) and without (+) precipitation influences. Confidence bands are included, $P = 0.05$.

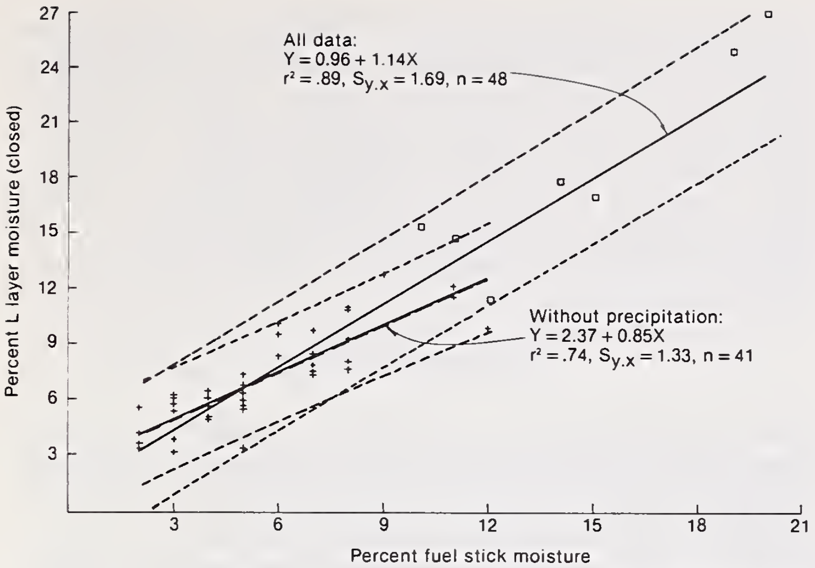

Figure 7.—Relationship of fuel stick moisture content and closed group L layer needle moisture content with (0) and without (+) precipitation influence. Confidence bands are included, *P* = 0.05.

this study site (Harrington 1981), are developed with a safety margin at each end of the moisture range. That way, even if the fuel moisture were either overestimated or underestimated, as long as other parameters were within the prescription limits, the fire should still burn safely and effectively.

H Layer Moisture Content

Deeming et al. (1977) gave representative examples of 100-hour timelag fuels as dead, roundwood fuels 1 to 3 inches in diameter and, very roughly, the forest floor from 0.75 to 4 inches below the surface. This forest floor depth would include the H layer from this study site. A regression of 100-h TL FM was made with actual H layer moisture contents taken the same day. The comparison from both open and closed groups are shown in figures 8 and 9.

There is fair agreement between the two variables in each of figures 8 and 9, but the calculated timelag moisture contents and actual fuel moisture contents fail to produce a one-to-one relationship. Possible reasons for this are:

(1) Although the humus layer may have a timelag of 100 hours under standard conditions described by Fosberg (1971), its position within the forest floor would make its response much different than if under the environmental conditions found in a weather shelter which are used in calculating 100-h TL FM. For example, the reduced evaporative potential in the lower horizons would allow a surface film of water to remain on the fuel longer and absorption to continue longer even though the upper horizons may be losing water (Simard 1968a).

(2) Because of the presence of structural water (water held between fuel particles), the moisture content of a humus layer can be more than 100%. The maximum 100-h TL FM calculated by the fire danger program presented by Burgan (1979) is 53%.

(3) Physical characteristics which influence moisture response time, such as bulk density and thickness, are certain to vary throughout the stand.

(4) Precipitation duration is used to calculate 100-h TL FM, but the lower layers of the forest floor are influenced not only by duration but also by precipitation rate (Fosberg 1971, 1979). As the rainfall rate increases, less of the water will be absorbed by the upper layers and more will pass through to the lower layers. In fact, a low-rate, short-duration rainfall will probably have no effect on the H layer other than by an increase in humidity.

As a result of these four conditions, the drying and wetting rates of the H layer humus and the calculated rates of 100-hour timelag fuels would not be equal.

Examples of these conditions are shown by the few widely dispersed data points in figure 8. All four points above and on the upper half of the regression line occurred shortly after substantial rainfall. Surface and structural water were probably present in the humus, but the 100-h TL FM was decreasing mainly because of a drop in average relative humidity. One of the two

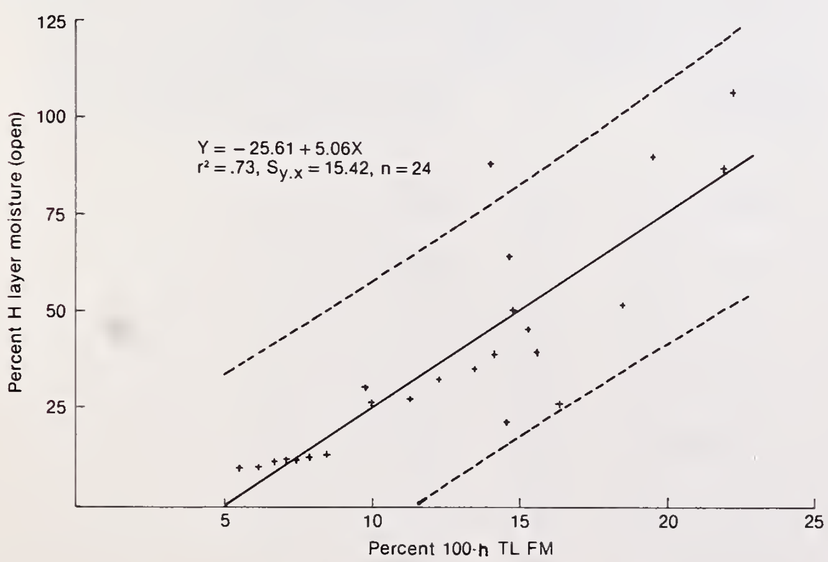

Figure 8.—Relationship of 100-h TL FM and open group H layer moisture content. Confidence bands are included, *P* = 0.05.

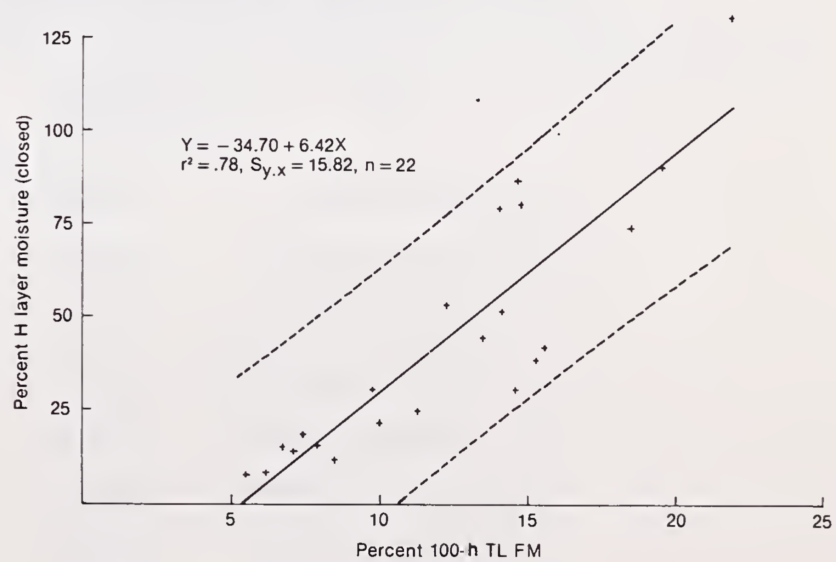

Figure 9.—Relationship of 100-h TL FM and closed group H layer moisture content. Confidence bands are included, *P* = 0.05.

data points which stand out below the regression line occurred after a rainfall of sufficient duration (4-hours) to cause an increase in the 100-h TL FM but not of sufficient quantity (0.01 inch) to reach and cause an increase in the H layer moisture content.

For precise determination of H layer moisture content using the 100-h TL FM, the equations developed here are marginally useful. For practical purposes, a rough estimate of the moisture content of this forest floor layer is all that is needed for prescribed burning. Moisture conditions which should be known are the upper limit where burning would be ineffective, the lower limit where burning would be hazardous, and, perhaps, an optimum range. These values are within the precision of the regressions and are being researched (Harrington 1981).

Moisture Content of Other Fuels

At this study site, woody fuels smaller than 3 inches in diameter make up a small portion of the total fuel loading (14%)[5] and, therefore, play a minor role in fire behavior. However, comparisons were made between the moisture contents of various size woody fuels and their corresponding calculated timelag moisture contents to test the predictability of actual fuel moisture (table 1). The F layer needles which occurred at depths of 0.50 to 1 inch should be representative of 10-hour timelag fuels (Deeming et al. 1977).

In general, the best correlations occurred between smaller fuel and shorter timelag moisture values. In each case, the regression slope was much greater than one indicating that the two variables did not have a one-to-one relationship. This lack of equality can be partially explained by the fact that the woody fuels were collected from the surface of the forest floor and, therefore, were influenced not only by the vapor pressure from the surrounding air but also from the forest floor below. In the NFDRS, fuel moisture contents are calculated from equilibrium moisture contents using weather shelter temperatures and humidities (Fosberg and Deeming 1971). Therefore, an aerial fuel situation is assumed. Also, the actual fuel moisture changed to a greater extent with precipitation than did the corresponding timelag fuel moisture. As in the regressions for estimating L layer needle moisture content, relationships between calculated and actual moisture contents were closer to unity when moisture values for fuels recently influenced by precipitation were removed.

Table 1.—Regressions comparing actual fuel moisture (*Y*) with corresponding timelag fuel moisture calculated from the National Fire-Danger Rating System (*X*)

Fuel	Timelag	Regression	r^2	$S_{y \cdot x}$	n
F layer needles (open)	10-hour	$Y = -16.04 + 3.73X$	0.74	13.81	22
F layer needles (closed)	10-hour	$Y = -19.05 + 5.00X$	.71	19.95	22
0- to 1/4-inch wood (open)	1-hour	$Y = -2.79 + 1.88X$	.89	2.71	20
0- to 1/4-inch wood (closed)	1-hour	$Y = -5.83 + 2.80X$	.86	4.60	20
1/4- to 1-inch wood (open)	10-hour	$Y = -16.44 + 3.55X$	.86	7.65	22
1/4- to 1-inch wood (closed)	10-hour	$Y = -17.02 + 4.00X$	.85	10.30	22
1- to 3-inch wood (open)	100-hour	$Y = -36.01 + 4.87X$	.62	19.15	24
1- to 3-inch wood (closed)	100-hour	$Y = -29.67 + 4.39X$	.65	15.83	24

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U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

Rocky Mountains

Southwest

Great Plains

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

Albuquerque, New Mexico
Bottineau, North Dakota
Flagstaff, Arizona
Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Lubbock, Texas
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526